TITLE:

Suspended Particle Characteristics in Storm Runoff from Urban Impervious Surfaces in Toowoomba, Australia

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Abstract

Total Suspended Solids as a measure of suspended particles in urban stormwater has limitations and the alternative Suspended Sediment Concentration method was adapted to determine Non-Coarse Particle (NCP) concentration, defined as particles smaller than 500 µm. NCP was partitioned into the following classes: Very Fine Particles (<8 µm, VFP), Fine Particles (8-63 µm, FP) and Medium Particles (63-500 µm, MP). A Site Mean Concentration approach was adopted to differentiate the suspended particle characteristics between three impervious surfaces (roof, road and carpark) using runoff data collected for 35 storms. Runoff particle size distribution (PSD) of all surfaces was dominated by particles less than 63 µm. A weak trend of relatively constant VFP concentration was present in the road runoff data. Roof runoff PSD became finer as NCP concentration increased and, overall, the PSD of carpark runoff was coarser compared to road and roof runoff. These findings have runoff treatment implications as settling processes are influenced by particle size.

1. Introduction

Pollution due to urban stormwater is a significant environmental issue. A management philosophy to reduce, detain, infiltrate, treat or use stormwater at its source has emerged to reduce the adverse impacts of urban stormwater. This approach is variously termed ‘low impact development’ (LID), ‘water sensitive urban design’ or ‘sustainable urban drainage systems’. A common LID feature is the strategic use of small-scale and on-site controls on urban stormwater, including non-structural measures such as alternative road layouts to minimize imperviousness. Several LID-type design guidelines are available (e.g. CIRIA, 2000 used in Scotland). The introduction of LID has highlighted a need for more information about the characteristics of stormwater generated from specific urban surfaces such as roads and roofs.

Suspended particle load in urban runoff is a key pollutant leading to reduced water clarity in receiving waters. Due to the affinity of heavy metals and other contaminants to particles, stormwater treatment systems generally involve some form of particle separation process. On this basis, Total Suspended Solids (TSS) is a common performance indicator used in urban stormwater planning and analysis. Determination of TSS concentration is accepted practice to characterise suspended particles in runoff, but research has disputed the validity of using TSS as a reliable measure in stormwater (Knott, et al. 1992; Gray, et al. 2000). An alternative measure, referred to as Non-Coarse Particle (NCP) concentration is described in this paper.

This paper is based on stormwater monitoring data collected from three impervious surfaces; a road, a carpark and a roof, located in Toowoomba, Australia (Brodie, 2007). The NCP test methods, the monitored impervious surfaces and a passive stormwater sampling device developed as part of the study are described.

Suspended particle characteristics in runoff from each surface are also described based on statistical analysis of the measured data. Site Mean Concentration (SMC) is often used to assign a representative pollutant concentration for stormwater planning purposes and requires averaging data for a given site (Adams & Papa, 2000). SMC is a simple method to predict pollutant loads from urban catchments and is incorporated in various hydrological models used in LID planning (Elliott & Trowsdale, 2007). In our paper, a SMC approach has been adopted to differentiate the suspended particle characteristics in runoff from the three impervious surfaces.

Definition of an appropriate average to use to determine a SMC is dependant on the type of statistical distribution of the measured data. This aspect was evaluated for NCP concentrations obtained for each impervious surface. The distribution and representative averages of particle load, size fractions and inorganic content of suspended particles were also derived and are discussed.

2. Study Methods

2.1 Determination of Suspended Particles in Storm Runoff

Stormwater quality studies have typically selected Total Suspended Solids (TSS) as the primary determinant of suspended particle concentrations in urban runoff. The suitability of the TSS test method (e.g. APHA, et al. 1998) in non-wastewater sample analysis, such as storm runoff, natural waters and river flows, has been the subject of considerable research particularly by the US Geological Survey (e.g. Knott, et al. 1992; Gray, et al. 2000; Selbig, et al, 2007). As part of the TSS method, an aliquot is taken from the collected sample and filtered. The extraction procedure, by pipetting, may under-represent ‘sand-sized’ particles (>63 µm) in the aliquot as sample mixing may not be adequate to maintain these particles in suspension. This introduces a bias in the TSS results, especially if the >63 µm fraction of the sample exceeds 25% by weight.

The Suspended Sediment Concentration (SSC) method was designed to overcome the bias introduced by the TSS method, by separating ‘sand-sized’ particles from the whole sample prior to subsampling. It has been confirmed that the use of the SSC method provides a more accurate suspended particle determination than the TSS method (USGS, 2000; Guo, 2007). SSC Test Method C (incorporating wet sieving filtration) covering concentration measurements of two particle size fractions; ‘fines’< 63µm and ‘sand’> 63µm (ASTM, 2002) was adapted for use in our study. In this method, the entire sample volume is passed through a 63 µm sieve to retain and measure the ‘sand’ particle mass, then thoroughly mixed, subsampled and filtered to determine the ‘fines’ concentration.

The first modification to the SSC method was to set an upper particle size limit of 500 µm for suspended matter in urban runoff. This limit has been previously used in a road runoff study comparing suspended solids data from Australia, United States and Europe (Lloyd & Wong, 1999) and guidelines for the evaluation of stormwater treatment technologies (WSDOE, 2002). A 500 µm threshold for particles in stormwater runoff was also used in an evaluation of street sweeping methods in Wisconsin, USA (Selbig & Bannerman, 2007). The specific focus of this paper is the study of particles less than 500 µm in size, referred to as Non-Coarse Particles (NCP). The term NCP was introduced to differentiate this measure of suspended solids from TSS and SSC which do not prescribe an upper particle size limit. Particles larger than 500 µm are designated Coarse and were not measured during the study.

Various aspects of urban stormwater are closely allied with particle size, including washoff response to storms, contaminant associations such as heavy metal adsorption and stormwater treatment processes and efficiency. It was thus considered important to further partition NCP into different size classes. Several classification systems have been used in past runoff studies (e.g. Ball, et al. 1994; Characklis & Wiesner, 1997; Madge, 2004) which vary in terms of the number of classes and the particle size range that define each class.

A particle classification was devised for our study starting with the SSC Test Method C use of 63 µm as a point of separation. The adopted system includes the following classes: Very Fine (<8 µm), Fine (8-63 µm) and Medium (63-500 µm). Approximately an 8-fold increase in particle size defines the boundary of each class and the class ranges are consistent with the particle size classification modified from Guy (1969) and recommended by Bent et al. (2000) for sediment analysis. Very Fine Particles (VFP) includes ‘very fine silts’ and ‘clays’, Fine Particles (FP) covers ‘fine silts’ to ‘coarse silts’ and Medium Particles (MP) covers ‘very fine sands’ to ‘medium sands’ under the Bent et al. (2000) system.

The SSC Test Method C was modified by including whole-sample wet sieving with a 500 µm screen prior to the 63 µm screening step. Two subsamples, each typically of 1L volume, were drawn from the screened water sample as it was thoroughly mixed with a churn splitter. Filtration of the subsamples was done in duplicate for quality assurance. For low concentration samples such as roof runoff, no subsampling was undertaken as this would have left inadequate residue mass after filtering. An 8 µm reusable filter was used to capture the FP fraction within each subsample and the filtrate was passed through a glass fibre filter to retain the residual VFP fraction. After drying in a 105ºC oven, the material from the 63 µm screening and filter residues were weighed to determine the MP, FP and VFP concentrations in the sample. The Standard Method 2540-E (APHA 1998) for fixed and volatile suspended solids was used to determine the inorganic content of each particle class.

2.2 Selected Impervious Surfaces

Three impervious surfaces less than 500 m^2 in drainage area located in Toowoomba were selected for monitoring purposes and includes a galvanised iron roof, a concrete carpark and an asphalt roadway. The surfaces are in close proximity to each other, as shown in Figure 1, in order to limit the effects of spatial variability in rainfall. The surfaces were selected on the basis that 1) each represent a common impervious surface found within an urban residential or commercial context, 2) are, as far as practical, homogeneous in surface material and topography, and 3) are discrete catchments that receive no external surface flows from other surface types.

As it is part of a residential house constructed in October 2004, the roof is a relatively new surface in good condition. The carpark is located at the rear of commercial premises that includes an orthodontic surgery and is utilized by staff and patients. Due to design of the surface drainage system, runoff from only a small proportion of the carpark could be intercepted for sampling. The area covers four car parking bays. The road surface is part of the inner city residential street network and incorporates a one-way, northbound roadway that handles approximately 3500 vehicles/day. The street has a two way crossfall and runoff from the eastern half of the street is sampled.

Further details of each individual surface are provided in Table 1. Each surface has the basic components of the surface itself subjected to particle washoff during storms and the surface drainage system that conveys runoff laterally to a single point of discharge (at which runoff samples were collected). No underground pipe drainage is present for the trafficable road and carpark surfaces, and all surface runoff is drained by the kerb. The roof surface is drained by a gutter to a single downpipe.

2.3 Runoff Sampling

A passive sampling device was installed at the point of discharge of each surface to collect and store a flow-weighted runoff sample for individual storms. Passive samplers have been used in previous urban runoff studies (e.g. Clarke, et al. 1981; Waschbusch, et al. 1999) and are not powered and rely on the physical flow of stormwater to obtain a sample.

The sampling device was designed to extract a continuous sample in constant proportion of the runoff discharge, giving a single composite sample suitable for the determination of the Event Mean Concentration (EMC) of the storm runoff. A schematic diagram of the device is shown in Figure 2 and includes 1) a main rectangular channel that conveys the runoff flow; 2) a main flow splitter consisting of two vertical walls which directs water via a slot into; 3) a secondary rectangular channel fixed under the main channel; and 4) a secondary flow splitter that directs sampled water flow into a sample container. Details of the development of the sampling device are provided by Brodie & Porter (2004).

The basis of the sampling device is the use of two flow splitters in series. Each flow splitter is centrally placed within the channel and extracts a vertical 'slice' of the runoff flow. This simple design allows the sampled flow to be isokinetic and vertically integrated with the runoff flow. Transport of particles larger than 40 μm is not uniform with flow depth (Bent, et al. 2000), and the vertical partitioning by the flow splitter provides representative sampling across a range of particle sizes. Hydraulic testing demonstrated that the sampling device is capable of obtaining a constant proportional sample flow (within ± 2%) for discharges up to 5 L/s. Sediment testing was also conducted and found that sampler performance is consistent with high frequency grab sampling at one minute intervals (Brodie, 2005).

At each surface discharge point, a screen or small trash rack was installed to intercept leaves and debris that may clog the flow splitters of the sampler. The screened flows were directed into the sampling device, which was housed in a locked box together with a 60 L plastic container to store the runoff sample. The sample storage capacity and the sampling ratio (sample volume:event runoff volume) of the flow splitter device were sized to handle the stormwater runoff volume associated with the 1-year average recurrence interval storm. A tipping bucket pluviometer with data logger was installed at the rear of the residential house as shown on Figure 1 to measure and store rainfall intensity data.

The runoff sample was retrieved from each sampling device as soon as practical after the end of a storm event. The volume of each sample was measured and laboratory determinations were made of VFP, FP, MP and hence NCP concentrations. The period of stormwater monitoring extended from December 2004 to January 2006. Rainfall data and event-composite samples were obtained for between 32 to 35 storms, depending on when each sampler started operating and the incidence of equipment failure. Event rainfalls varied from 2.5 mm to 64.3 mm, at average intensities ranging from 1 mm/hr to 40 mm/hr.

2.4 Statistical Analysis to Characterise Suspended Particles

All statistical analyses in this paper are performed using R (R Development Core Team, 2007). As an average of NCP EMCs, the Site Mean Concentration (SMC) depends on the type of data distribution. TSS data obtained for urban catchments have been found to follow a log-normal distribution (Athayde, et al. 1983; Van Buren, et al. 1997; Duncan, 1997). As the analytical methods differ, there is no direct relationship between TSS and SSC, and the data obtained from the two methods are not directly comparable (Gray, et al. 2000). An evaluation of a stormwater treatment system at Green Bay, Wisconsin USA by Horwatich, et al. (2004) found significant variations in the ratio of TSS to SSC (0.49-1.25 for inflow data, 0.47-3.0 for outflow data). It was thus considered appropriate to check if the SSC-based NCP concentration data also conforms to a log-normal distribution. The Shapiro test for normality (Conover, 1999) was used for this purpose.

For data having a log-normal distribution, the mean of log-EMC values in real space is an appropriate measure of central tendency and thus SMC. For normally distributed data, an arithmetic mean was used as an SMC. The Site Mean approach was extended to incorporate other particle characteristics, namely load, particle size fraction and inorganic content.

Analyses were performed to determine if differences in particle characteristics are statistically different between surfaces. One-way ANOVA *F*-tests were performed to compare groups (such as surfaces) and pairwise *t*-tests were conducted to determine the location of the differences, correcting the P-values for multiple comparisons using the method of Holm (1979). A 5% significance level (P-value=0.05) was adopted in our analysis. Regression relationships between VFP, FP and MP concentrations with NCP concentration were also explored.

3. Suspended Particle Characteristics of Impervious Surface Runoff

3.1 EMC Statistics

EMC is directly determined by laboratory analysis of the flow-weighted composite samples collected at each impervious surface. Log-normal probability plots of NCP concentration (<500 µm, equal to sum of VFP, FP and MP) for the roof, carpark and road surfaces are given in Figure 3. There is one very high value for the EMC roof data, almost three times larger than the next highest observation. On investigation, this NCP concentration was attributed to a major dust storm that coincided with the rainfall that occurred on February 2, 2005. Concentrations of airborne particles smaller than 10 µm (PM_{10}) reaching 136 $\mu g/m^3$ were measured at a nearby air monitoring station during the event, compared to ambient PM_{10} values generally less than 20 $\mu g/m^3$. This outlier demonstrates that relatively high particle concentrations (in this case, NCP =155 mg/L) can occur in roof runoff due to infrequent meteorological events such as dust storms. This observation was deleted as it comes from a different population that the rest of the data and was excluded from the statistical analyses of the roof data.

Shapiro test results suggested there was no evidence to doubt the normality assumption of the log-data. P-values for the three surfaces are provided in Table 2 and exceed the adopted significance level of 0.05. Accordingly, SMC values given in Table 2 are based on the mean of log-EMC values in real space. The two standard deviation range converted to real space is also provided for each surface (i.e. mean±1 S.D), in addition to the actual data range (minimum - maximum). The measured range in NCP EMC is substantial, with between a 10 to 60-fold variation between minimum and maximum values depending on the surface.

Boxplots presenting measured NCP concentrations for the three surfaces are provided as Figure 4. The plots show visually that NCP concentrations are significantly higher in the road runoff, and significantly lower for the roof runoff and this was confirmed statistically (*t*-tests with Holm (1979) corrected P-values from all pairwise comparisons < 0.0001).

3.2 Particle Load Statistics

Event runoff volumes were computed using the DRAINS hydrological model (O'Loughlin & Stack, 2003) using the measured rainfall for each storm. Initial losses were based on investigations of small-scale urban impervious surfaces by Goyen & O'Loughlin (1999) and set at 1 mm for the road and carpark and 0.5 mm for the roof. As a flow-weighted average, the sample volume that was captured provided a measure of the amount of runoff generated from each surface and this data was used to validate the predicted volumes.

The measured EMC and the estimated runoff volume were multiplied to determine the particle load per unit area (in mg/m^2) washed off the impervious surfaces during each storm. NCP load statistics (mean of log-load values or Site Mean Load and two standard deviation range, in real space) are provided in Table 3. Shapiro P-values are also provided in Table 3 and indicate that the NCP loads follow log-normal distributions (P-values>0.05). This justifies the use of the log-based Site Mean Load as an appropriate measure of central tendency. Based on an ANOVA, the road generated significantly higher NCP loads, and the roof NCP load was significantly lower compared to the carpark runoff (all corrected pairwise P-values are less than 0.0001). Consistent with the NCP EMC data, a wide range of NCP load values was present for all surfaces.

3.3 Particle Size Fraction Statistics

The determination of VFP, FP and MP concentrations provide a bulk measure of particle size distribution when expressed as a percentage by mass of the NCP concentration. Percentage fractions of each particle class were determined from the measured data. Shapiro tests were performed to identify if the various particle size fractions fit a log-normal distribution. The results were mixed, as a logarithmic transformation was applicable to VFP, but not FP. For MP, using a logarithmic transformation was inconclusive: it was useful for the road data but not needed for the other surfaces. For simplicity, arithmetic means were used to derive the average fraction for each particle class and these statistics are provided in Table 4.

The class fractions were statistically analysed to identify differences (P-value <0.05) between surfaces. Carpark runoff tends to have lower proportions of FP, and higher proportions of MP. Road and roof runoff had similar proportions of MP and FP, but roof runoff had a higher proportion of VFP. Statistically significant differences in particle class fractions between surfaces are denoted (as letters a and b) on Table 4.

The FP (8-63 μm) class represented the largest proportion of NCP mass for all surfaces. The average FP fraction varied from 48% for carpark runoff to 63% for road runoff. The smallest proportion of NCP was associated with VFP (<8 μm), constituting on average less than 20% by mass. By averaging a combination of VFP and FP concentration data, NCP was consistently dominated by particles smaller than 63 μm which varied from 68% (carpark) to approximately 78% (roof and road) of the total particle mass. Other studies have identified a dominance of 'fine' particles (nominally less than 100 μm) in road runoff, including Lloyd & Wong (1999) based on compiled Australian data, Memon & Butler (2005) who determined particle size distributions in runoff from an East London road and work by Li et al. (2005) at highway sites at Los Angeles, USA.

3.4 Particle Class Concentration Regressions

Relationships between VFP, FP and MP EMC with NCP EMC were also explored. This was done to check if the various particle concentrations were in direct proportion to NCP. The form of these inter-relationships can be seen from the log-plots of the concentration of each particle class with NCP for the three surfaces, provided as Figure 5. Power regressions of the form $Y= \alpha X^{\beta}$ were obtained by linearizing the equation and fitting a linear regression model; the regression statistics are provided in Table 5. High correlations (R^2 >0.9) were obtained in the cases of roof FP and VFP, carpark MP and FP, and road FP power relationships with NCP EMC.

The magnitude of the exponent β in the power regression provides useful information about the variation of particle class concentrations with NCP. As β tends to zero, particle concentration approaches a relatively constant value independent of the NCP EMC. A value of β close to 1 indicates that the particle class concentration is in direct proportion to the NCP concentration (i.e the particle class fraction is relatively constant). The hypotheses β=0 and β=1 were tested statistically using a *t*-test, and the resulting P-values are also provided in Table 5.

Road VFP had no statistically significant relationship with NCP (β=0): mean road VFP remained almost constant, though a large amount of scatter is evident about the regression line. This outcome is consistent with Furumai, et al. (2002) who found similar results for TSS data measured from a highway at Winterthur, Switzerland. In their study, the concentration of particles less than 45 µm approached a constant concentration as TSS increased. However, the small correlation coefficient ($R^2<0.1$) indicates significant scatter is present in the road VFP EMC data. For all other surfaces and particle classes, the parameter β is statistically different to zero (P-value<0.01 in all cases).

A trend of road MP EMC data being in direct proportion to NCP EMC (β =1) was not contradicted by the data. This was also the case for carpark FP EMC data, though the statistical significance was marginally below the adopted 5% level. These results differ to the conclusion for road VFP, suggesting different runoff processes occurred for VFP compared to FP and MP.

A β value greater than 1 indicates a greater dominance of a particle class with increasing NCP concentration. On this basis, the particle size distribution in carpark runoff becomes 'coarser' with high NCP concentration as MP β exceeds 1 (β=1.38) and β coefficients for FP and VFP are significantly less than 1 statistically. Road runoff may also become slightly 'coarser' as NCP concentration increases, although this effect is not significant (as road MP β =1.19 is statistically not different than 1). The study by Furumai, et al. (2002) concluded that samples of road runoff with high TSS concentrations had a coarser distribution of particle sizes, although their results produced significantly greater β values (e.g. β=2.06 for 106 to 250 μm particle class). This difference in results may be due to the Furamai et al. (2002) study collecting most of the road runoff samples during the initial first flush period.

In contrast, the particle size distribution in roof runoff becomes 'finer' with high NCP concentrations as MP β is significantly less than 1 (β=0.76).

3.5 Inorganic Content Statistics

The inorganic content of each particle class was determined by the fixed suspended solids laboratory analysis and is expressed as a percentage mass. Shapiro tests indicated that the inorganic content has an approximate normal distribution for each surface for all particle fractions ($P>0.05$). Accordingly, the arithmetic mean and standard deviation of the measured inorganic contents are provided in Table 6 as the measure of central tendency. Sansalone & Tittlebaum (2001) determined a 71% mean inorganic content for highway runoff at Louisiana, USA using data collected from 9 storms. This is comparable with the 75% mean derived for the Toowoomba road NCP inorganic content, but is significantly higher than the 45% median determined by Gromaire-Mertz, et al. (1999) for street runoff from 7 storms within central Paris, France. A median 61% inorganic content for roof TSS was also reported by Gromaire-Mertz, et al. (1999), which is consistent with the mean 63% inorganic content of NCP shown in Table 6.

Boxplots of NCP inorganic content data for the three impervious surfaces are presented in Figure 6. For NCP and all particle classes VFP, FP and MP, the inorganic content of carpark and roof runoff does not differ significantly according to an ANOVA *F*-test. The inorganic content of road runoff is significantly higher for all particle classes. An ANOVA *F*-test was also conducted to establish the differences between particle class inorganic content for each individual surface. These differences are denoted (as letters a and b) on Table 6. Numerically, FP has the highest inorganic content for each of the surfaces, but the analysis suggests that this is statistically true (P-value<0.05) for the road only. In all cases, the FP inorganic content was significantly greater than the VFP inorganic content.

4. Conclusions

Several conclusions can be made based on statistical analysis of suspended particle data collected for three impervious surfaces in Toowoomba, Australia:

1) NCP (<500 μm) EMC data followed a log-normal distribution for all surfaces. A suitable measure of an 'average' NCP concentration or Site Mean Concentration (SMC) is thus based on the mean of log-EMC values converted to real space. Site Mean Load (SML), or the mass loading of NCP per unit area, was also log-based for all surfaces. In increasing order, the SMC and SML values for each surface were: roof (8.5 mg/L, 115 mg/m^2) < carpark (39 mg/L, 450 mg/m^2) < road (190 mg/L, 2070 mg/m^2).

2) SMC and SML provide planning-level measures of NCP generation, but should be used with caution given the substantial range in measured EMC data for all surfaces.

A 10 to 60-fold difference between the minimum and maximum EMC was present in the measured data.

3) FP (8-63 μm) represented the largest proportion of particle mass for all surfaces, constituting between 48 to 63% of the NCP mass, on average. The average VFP (<8 μm) fraction of NCP ranged from 15% for road runoff to 20% for roof runoff. Carpark runoff tended to have a low proportion of FP mass, and a corresponding high proportion of MP (63-500 μm) mass relative to the other surfaces. This suggests that the particle size distribution (PSD) of carpark runoff was generally 'coarser' than the PSD of road and roof runoff. However, the PSD in runoff from all surfaces was dominated by particles less than 63 μm in size.

4) Based on exponential regression analysis, VFP concentration in road runoff was relatively constant, even in the high NCP EMC range. Contrary to previous research, there is no evidence to suggest that the PSD of road runoff was significantly 'coarser' with increased particle concentration. It was found that the roof runoff PSD became 'finer' in the upper range of measured NCP concentration. These trends have implications in the treatment of runoff from these surfaces as settling processes are very dependant on particle size.

5) Inorganic content of all particle classes are normally distributed and arithmetic means were used to define average or representative values. Inorganic content of road NCP (mean 75%) was significantly higher than that of roof and carpark NCP (63% and 58%). This was also the case for the inorganic content of the particle classes MP, FP

and VFP. For all surfaces, the FP inorganic content was greater than the VFP inorganic content.

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Table 1: Description and geometry of the roof, carpark and road surfaces and their drainage systems

Feature	Roof	Carpark	Road
Surface type	Corrugated galvanised iron sheeting	Concrete	Asphalt pavement
Surface area and slope	51.8 m^2, 47%	56.2 m^2, 6.3%	450 m^2, 5%
Type of surface drainage	Baked paint steel roof guttering, 150mm wide	Concrete kerb, no gutter	Concrete kerb, no gutter
Length and slope of surface drainage	16.6m, <0.1%	4.8m, 0.8%	75m, 0.9%

Table 2: NCP EMC statistics for the roof, carpark and road surfaces

Surface	Shapiro P-value	SMC (mg/L)	±1 S.D. Range (mg/L)	Range (mg/L)
Roof	0.41	8.5	3.5-21	1.6-56
Carpark	0.53	39	15-105	6.2-354
Road	0.41	190	101-356	56-641

SMC = Site Mean Concentration, S.D. = standard deviation

Table 3: NCP Load statistics for the roof, carpark and road surfaces

Surface	Shapiro P-value	SML (mg/m^2)	±1 S.D. Range (mg/m^2)	Range (mg/m^2)
Roof	0.20	115	50-270	32-1114
Carpark	0.15	450	170-1210	56-2604
Road	0.90	2070	850-5020	161-7570

SML = Site Mean Load, S.D. = standard deviation

Table 4: Particle class fraction statistics for the roof, carpark and road surfaces, as percentage of NCP EMC

Particle class	Roof	Carpark	Road	ANOVA P-value*
MP	22±9 a	34±18 b	23±12 a	0.0006
FP	59±9 a	48±12 b	63±15 a	0.0004
VFP	20±5 a	16±13 a,b	15±15 b	0.0223

Arithmetic Mean ± Standard Deviation in %. Fractions of each particle class that are significantly different between surfaces (data across the rows) are indicated by letters (a and b). Using the VFP data as an example, the VFP fractions for the roof and road are significantly different, whereas the carpark VFP fractions are not significantly different to both the roof and road VFP fractions. *The P-values apply only for differences between surfaces for each particle class.

Table 5: Parameters of the regression model $Y = \alpha X^{\beta}$ fitted to NCP EMC (Y) and particle class EMC (X), plus the correlation coefficient R^2. The P-values in bold are non-significant at the nominal 5% level.

	Statistics	MP	FP	VFP
Roof	α	0.34	0.47	0.28
	β	0.76	1.10	0.82
	P-value; $\beta = 0$	< 0.0001	< 0.0001	< 0.0001
	P-value; $\beta = 1$	0.0017	0.0146	0.01012
	R^2	0.70	0.98	0.94
Carpark	α	0.073	0.738	0.772
	β	1.38	0.88	0.52
	P-value; $\beta = 0$	< 0.0001	< 0.0001	0.0020
	P-value; $\beta = 1$	0.0002	0.0456	0.0032
	R^2	0.89	0.93	0.42
Road	α	0.074	0.200	7.574
	β	1.19	1.21	0.19
	P-value; $\beta = 0$	< 0.0001	< 0.0001	**0.4303**
	P-value; $\beta = 1$	**0.1995**	0.0224	0.0031
	R^2	0.69	0.92	0.04

Table 6: Inorganic content statistics for the roof, carpark and road surfaces

Particle class	Roof	Carpark	Road
NCP	62±7.4	58±13	75±6.4
MP	58±18 a, b	58±11 a, b	69±9.8 b
FP	64±10 a	61±12 a	76±8.0 a
VFP	53±15 b	48±17 b	69±9.0 b
ANOVA P-value*	0.0701	0.0153	0.0259

Arithmetic Mean ± Standard Deviation in mg/L, Inorganic contents that are significantly different between particle classes for each surface (data down the columns) are indicated by letters (a and b). Using the roof data as an example, the FP inorganic content is significantly different to the VFP inorganic content, whereas the MP inorganic content is not significantly different to both the FP and VFP inorganic contents. *The P-values apply only for differences between particle classes for each surface. Across the rows, the inorganic content of road runoff is different to roof and carpark runoff at the 5% level for all particle classes.

Figure 1: Site plan showing monitored urban impervious surfaces.

Figure 2: Long section and cross section views of flow splitter sampling device (Not to scale, approximate width of main channel is 150 mm)

Figure 3: Log-normal probability plots of NCP EMCs for roof, carpark and road surfaces. The outlier in the roof data is at the right.

Figure 4: Boxplots of NCP against surface, plotted on the log scale. (The limits of the box represent the lower and upper quartiles, and the solid horizontal line represents the median. The horizontal lines at the extremes show the minima and maxima.)

Figure 5: Linear relationships between the particle concentration and NCP EMC for each surface and particle size, plotted on the log scale. Note the scale on the horizontal axis for the road is different to that used for the roof and carpark

Figure 6: Boxplots of the percent inorganic content of NCP by surface.

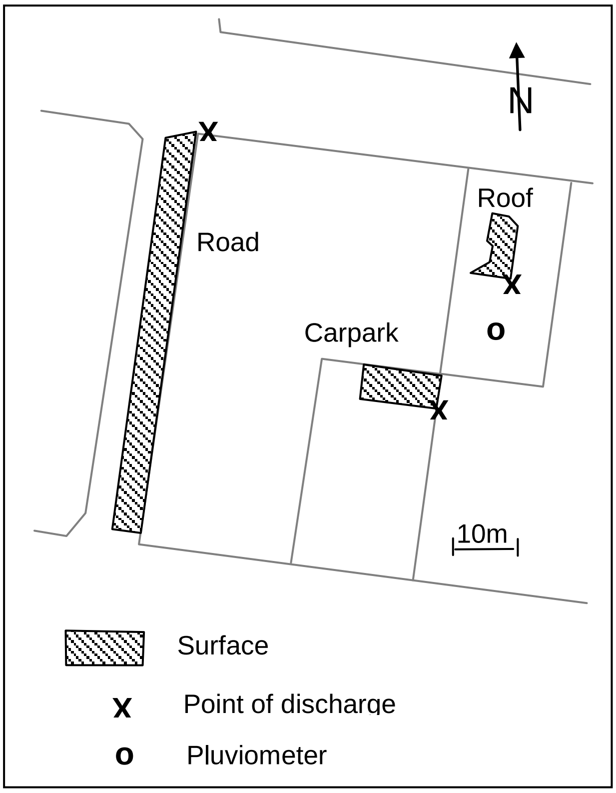
N
Roof
Road
Carpark
10m
Surface
x Point of discharge
o Pluviometer

Figure 1

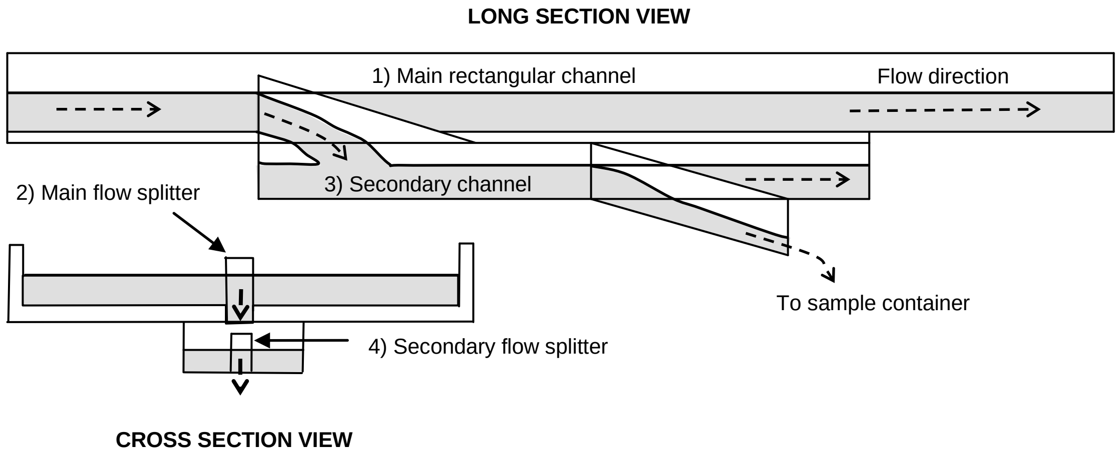
LONG SECTION VIEW
1) Main rectangular channel
Flow direction
2) Main flow splitter
3) Secondary channel
To sample container
4) Secondary flow splitter
CROSS SECTION VIEW

Figure 2

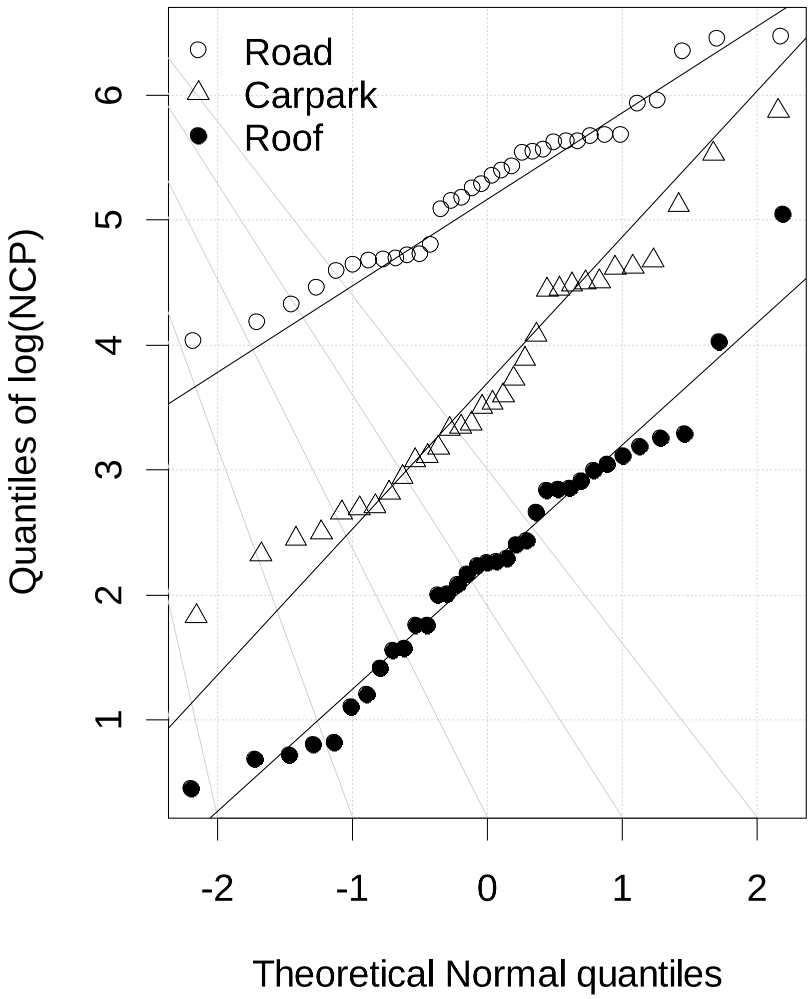
Road
Carpark
Roof
Quantiles of log(NCP)
6
5
4
3
2
1
-2
-1
0
1
2
Theoretical Normal quantiles

Figure 3

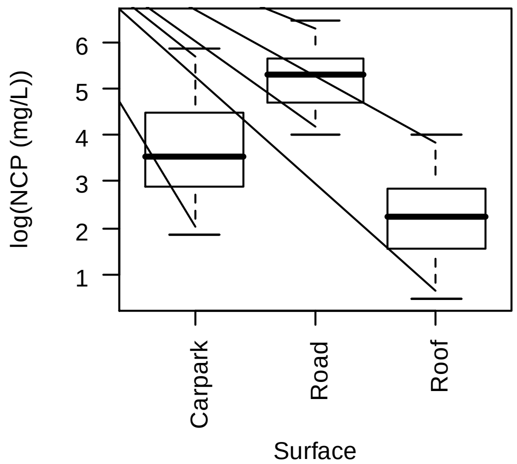

Figure 4

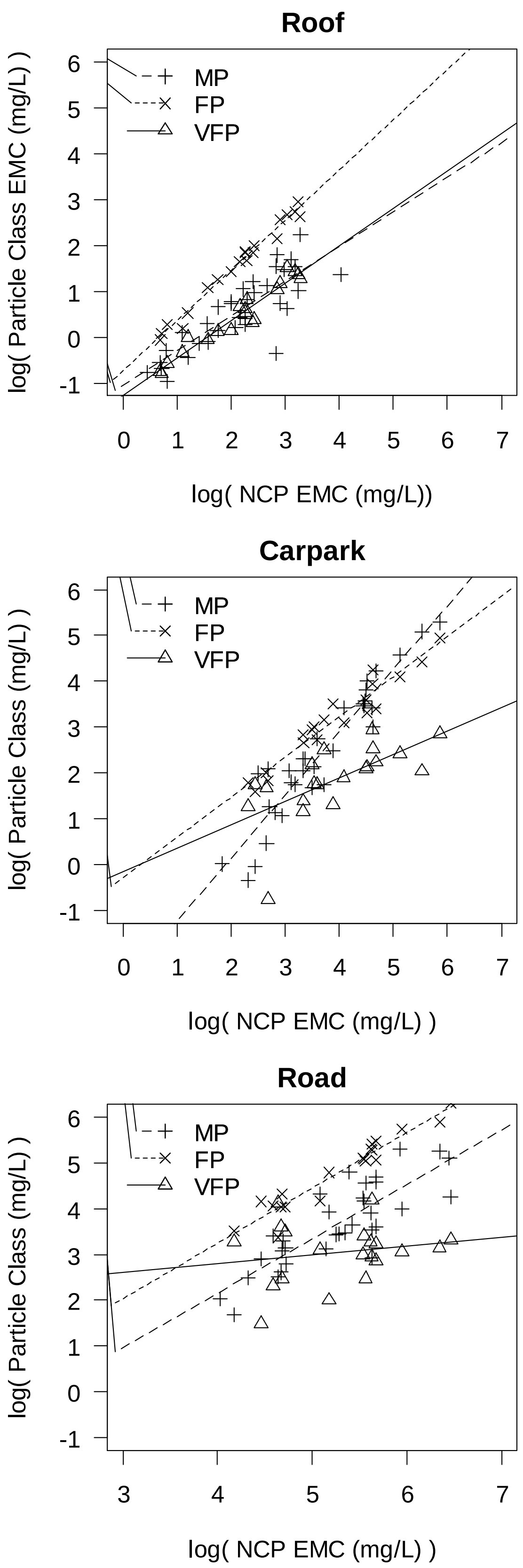
Roof
MP
FP
VFP
log(Particle Class EMC (mg/L))
log(NCP EMC (mg/L))
Carpark
MP
FP
VFP
log(Particle Class (mg/L))
log(NCP EMC (mg/L))
Road
MP
FP
VFP
log(Particle Class (mg/L))
log(NCP EMC (mg/L))

Figure 5

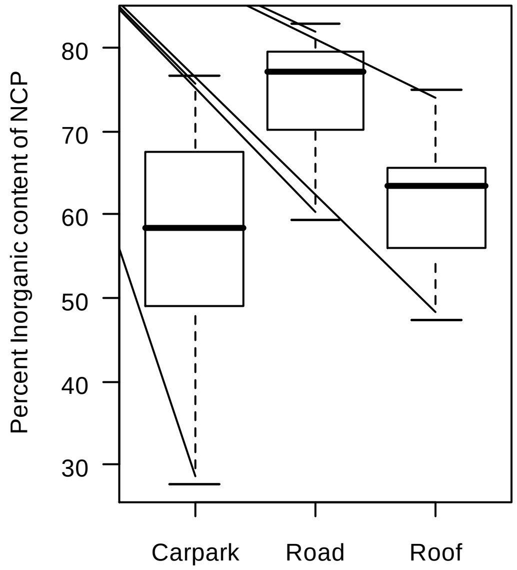
Percent Inorganic content of NCP
80
70
60
50
40
30
Carpark
Road
Roof

Figure 6